GRASSROOTS JOURNALS

Grassroots Journal of Natural Resources, Vol.7 No.3 (December 2024)
ISSN: 2581-6853 | CODEN: GJNRA9 | Published by The Grassroots Institute
Website: https://grassrootsjournals.org/gjnr | Main Indexing: Scopus and WoS

ISSN 2581-6853 | 7(3) Dec 2024

M – 00460 | Review & Analytical Article

Problems and Prospects of Realizing the Bioenergy Potential of Ukraine

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How to cite this paper: Pecheniuk, A., Garasymchuk, I., Pantsyr, Y., Potapskyi, P., Vusatyi, M., Olenyuk, A. and Nesterenko, V. (2024). Problems and Prospects of Realizing the Bioenergy Potential of Ukraine. *Grassroots Journal of Natural Resources*, 7(3): 223-243. Doi: https://doi.org/10.33002/nr2581.6853.070313

Received: 19 October 2024
Reviewed: 05 December 2024
Provisionally Accepted: 13 December 2024
Revised: 19 December 2024
Finally Accepted: 22 December 2024
Published: 31 December 2024
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Abstract

The article examines the key challenges facing the Ukrainian energy sector and explores global energy development trends in the 21st century, emphasizing the growing importance of bioenergy. It highlights Ukraine's significant bioenergy potential, driven by the availability of diverse biomass resources such as agricultural residues, forest biomass, energy crops, livestock waste, and industrial organic waste. A list of fast-growing energy crops suitable for cultivation in Ukraine is provided, alongside an analysis of key biomass-to-energy conversion technologies, including anaerobic fermentation, pyrolysis, gasification, combustion, fermentation, and esterification. The article underscores the strategic advantages of advancing bioenergy in Ukraine, including reduced dependence on imported energy, environmental benefits, rural development, job creation, increased investment attractiveness, and technological modernization of the energy sector. However, it also identifies significant barriers hindering the growth of the bioenergy industry, such as insufficient financing, outdated infrastructure, technological gaps, ineffective legislation, and competition from imported energy sources. To overcome these challenges, the article recommends adopting best practices from countries with successful bioenergy programs, including state and local budget subsidies, tax incentives, government investments, and grants for infrastructure development. It calls for a comprehensive strategy to support the industry, focusing on developing bioenergy infrastructure, simplifying licensing and regulatory processes, establishing national standards for bioenergy installations, and ensuring environmental compliance. Additionally, it emphasizes the need for research funding, support for startups and innovative companies, and attracting international investors and partners through participation in global technology exchange programs. These measures aim to unlock Ukraine's bioenergy potential and enhance its energy sustainability.

Keywords

Bioenergy; Ukraine; Energy infrastructure; Renewable energy; Biomass-to-energy technologies

Introduction

Energy is a fundamental component of modern society, ensuring the stable functioning of the economy, industry, transportation, and the daily lives of individuals. Reliable and accessible energy resources drive industrial growth, infrastructure modernization, investment activity, and job creation, and enhance the global competitiveness of nations. Moreover, energy significantly improves living standards by facilitating access to modern technologies and services.

The energy sector is also a key driver of innovation, particularly in the development of renewable energy sources, smart grids, energy storage systems, and energy-efficient solutions. However, challenges such as climate change, depletion of natural resources, and the increasing global demand for energy compel nations to seek sustainable approaches to energy development. In Ukraine, the energy sector plays a crucial role in ensuring the stability of the national economy. However, it faces numerous challenges, including high dependence on imported energy resources, outdated infrastructure, low energy efficiency, reliance on environmentally harmful coal, insufficient development of renewable energy sources, and systemic corruption. These issues have been exacerbated by the full-scale Russian invasion in 2022, which caused significant destruction to the energy infrastructure, the loss of generation capacity, and intensified the energy crisis. In this context, the development of bioenergy emerges as a critical and promising pathway to address Ukraine's energy challenges. Bioenergy sector refers to the industry and associated activities focused on the production, development, and utilization of energy derived from biological sources such as biomass, biogas, and biofuels. Bioenergy relies on the utilization of local resources, such as agricultural residues, forestry by-products, organic industrial waste, energy crops, and biogas. Harnessing these resources can significantly reduce Ukraine's dependence on imported natural gas and coal, lower greenhouse gas emissions, and enhance the stability of the energy system, particularly in times of crisis (Lisovyi, 2023).

The importance of bioenergy for Ukraine is multifaceted. Firstly, it strengthens energy independence by reducing reliance on external energy supplies. Secondly, bioenergy development stimulates the local economy by creating jobs in rural areas, enhancing infrastructure, and attracting investments. Thirdly, it has significant environmental benefits, including waste reduction and the mitigation of harmful emissions. Finally, bioenergy contributes to the modernization of the energy sector and facilitates Ukraine's integration into the European energy market. Furthermore, bioenergy plays a pivotal role in enhancing the resilience of Ukraine's energy system in the face of military and economic challenges. The use of local resources minimizes risks associated with disrupted imports and supports the recovery of regions affected by the war. Given its substantial potential and multifaceted impact, exploring effective strategies for bioenergy development is an urgent task for strengthening Ukraine's energy security, modernizing its energy infrastructure, and ensuring sustainable development in the face of contemporary challenges (Lutkovska and Zelenchuk, 2021). Energy is a fundamental driver of modern society, underpinning the stable operation of economies, industries, transportation systems, and daily life. Accessible and reliable energy resources fuel industrial growth, expand infrastructure, stimulate investment, create jobs, and enhance

the global competitiveness of nations. Additionally, energy plays a crucial role in improving living standards, providing essential services, and facilitating technological progress. In recent decades, the energy sector has become a catalyst for innovation, driving the development of renewable energy sources, smart grids, energy storage solutions, and energy-efficient technologies. These advancements aim to reduce dependence on traditional fossil fuels and support the global shift toward sustainability. However, this progress also demands new strategies to address environmental concerns and improve energy efficiency (Kostenko and Zghurovets, 2023).

According to Pryshliak (2021a), several key trends are shaping the 21st-century energy landscape: preference for high-quality fuels and efficient infrastructure; such as oil and gas pipelines and decentralized energy systems; growing reliance on established infrastructure, with increasing demands for expansion; development of adaptable energy systems equipped with flexible mechanisms; gradual reduction in dependence on oil and gas, with renewable energy sources playing a larger role in the energy mix; increased adoption of biofuels and renewable energy technologies and expansion of decentralized energy solutions, particularly in urban areas and agricultural regions.

Challenges in the Development of Ukraine's Energy Sector

In Ukraine, the energy sector plays a vital role in the national economy, but it faces numerous challenges that hinder its development and efficiency. These challenges span technical, economic, environmental, and political domains:

Dependence on Energy Imports. Ukraine relies heavily on imported energy resources, particularly natural gas and oil. Historically, the country sourced a significant portion of its gas from Russia, creating both energy and political dependencies. Despite efforts to diversify energy supplies and boost domestic production, reliance on imports remains a critical issue (Tyravskyi, 2021).

Outdated Infrastructure. Much of Ukraine's energy infrastructure is obsolete and in dire need of modernization. This results in low energy efficiency, high transmission losses, and frequent system failures. The reluctance of policymakers to implement necessary reforms and establish competitive energy markets has further exacerbated these issues. Additionally, corruption and mismanagement in state-owned enterprises continue to degrade the country's energy assets (Tyravskyi, 2021).

Low Energy Efficiency. Ukraine is one of the most energy-intensive economies globally, consuming significantly more energy per unit of GDP than developed nations. This inefficiency is linked to outdated technologies, poor insulation of buildings, and losses in electrical networks, making energy consumption in both industry and households highly inefficient (Huch-Denysenko, 2020).

Reliance on Coal. Coal-fired power plants generate a substantial portion of Ukraine’s electricity, but this dependency is environmentally damaging and economically unsustainable. Many coal mines are located in conflict zones, particularly in the Donbas region, leading to unstable coal supplies and increased greenhouse gas emissions. The

war has further disrupted coal production, with less than half of Ukraine's state-owned mines operational as of 2024 (Demchenkov, 2023).

Slow Development of Renewable Energy. Despite significant potential in solar, wind, hydro, and bioenergy, Ukraine's renewable energy sector has developed slowly. After a brief period of growth, investment in renewables declined, partly due to high upfront costs, limited government support, and regulatory instability. The ongoing war with Russia has further hampered progress, destroyed infrastructure and created market uncertainties (Konechenkov, 2022).

Corruption and Inefficient Management. Corruption and poor governance are persistent issues in Ukraine's energy sector. Lack of transparency, exploitation of state resources, and mismanagement have led to significant financial losses that could have been used for modernization and innovation (Kurtiev, 2022).

Impact of Military Conflict and Political Instability. Russia's full-scale invasion of Ukraine has severely damaged the country's energy sector, with losses estimated at $56.5 billion. Key infrastructure, including power plants, transmission lines, and oil and gas facilities, has been destroyed or occupied, further destabilizing the sector. The occupation of the Zaporizhzhya Nuclear Power Plant and the destruction of hydroelectric plants have compounded the crisis (Kyiv School of Economics, 2024).

Key Challenges in Ukraine's Energy Security

Biriukov (2024) highlights five critical challenges facing Ukraine's energy sector. These include 1) vulnerability of energy infrastructure to military attacks; 2) Dependence on imported energy resources; 3) Technological obsolescence within the industry; 4) Insufficient development of renewable energy; 5) Inefficient energy consumption; and 6) Promising Pathway: Bioenergy Development. One of the most promising solutions to Ukraine's energy challenges is the development of bioenergy. By utilizing local resources such as agricultural waste, forest residues, and biogas, Ukraine can reduce its dependence on imported energy, particularly natural gas and coal. Bioenergy offers a sustainable and resilient energy source, especially critical during periods of conflict and economic instability. Moreover, it aligns with global trends toward renewable energy and supports the country's transition to a green economy.

The main objectives of the study were:

- to assess the current state and development trends of the bioenergy sector in Ukraine;
- to evaluate the availability of raw materials used for bioenergy production in Ukraine;
- to analyze the efficiency and potential for improving biomass conversion technologies for energy production.

Methodology

This study is based on theoretical and methodological foundations rooted in the ecological and economic approach to renewable energy development, supported by

findings from prior scientific research in the field of bioenergy (Pecheniuk, 2024). A range of research methods was applied to achieve the study's objectives:

- *Logical Method.* The logical method was used to substantiate the benefits of effective bioenergy production for citizens, enterprises, regions, and the state. This involved summarizing global energy trends and addressing key challenges within Ukraine's energy sector, as outlined in Biriukov (2024).
- *Classification Method.* The classification of energy crops used in Ukraine's bioenergy production was based on the method used by Pryshliak (2021a), offering a structured understanding of the crops' role in the sector.
- *Systems Analysis of Energy Crop Advantages.* A systematization of the advantages of cultivating energy crops in Ukraine was conducted, incorporating forecasts developed by researchers at the Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine (Heletukha, 2022).

By integrating these methods, the study provides a robust framework for understanding the current state, challenges, and opportunities within Ukraine's bioenergy sector and offers actionable recommendations for its sustainable development.

Results

Analysis of the Bioenergy Industry in Ukraine

Bioenergy, a crucial sector of renewable energy, harnesses biomass to generate power. Amidst global climate change, reliance on imported energy resources, and the pressing need to enhance energy efficiency, advancing bioenergy in Ukraine emerges as a strategic priority. Ukraine's bioenergy potential is significant, and its effective use can make a significant contribution to ensuring the country's energy independence.

Bioenergy projects can be implemented locally, which contributes to the decentralization of energy supply. This enhances the energy system's ability to withstand and adapt to disruptions in infrastructure and reduces reliance on large, centralized power plants that are easy targets for attacks. In addition, bioenergy production can stimulate the growth and strengthening of regional economies, especially in rural areas, by creating new jobs. This includes growing energy crops, collecting waste for recycling and operating bioenergy plants. Harnessing bioenergy helps to lower greenhouse gas emissions, which is important for improving the ecological situation and fulfilling Ukraine's international climate obligations. It significantly curtails reliance on coal, the dirtiest energy source. Investments in bioenergy can become part of broader reforms of Ukraine's energy infrastructure. This will open access to the latest technologies, attract investments and contribute to the diversification of the energy balance (Pecheniuk, 2024).

Ukraine boasts a robust agricultural industry, offering substantial potential as a source of biomass for energy generation. This makes it possible to use agricultural waste, which is now often simply burned or disposed of, to produce energy. Thus, advancing bioenergy in Ukraine will not only ensure a more stable and cleaner energy supply but also increase the country's energy security, promote economic growth and help solve environmental problems. Key sources driving bioenergy production in Ukraine include:

biomass of agricultural origin, forest biomass, energy crops, livestock waste, and industrial organic waste.

Agricultural biomass remains the main component of biomass energy potential in Ukraine. Ukraine is an agrarian country, which provides significant opportunities for the use of agricultural waste, such as straw, corn stalks, residues of grain and oil crops. This facilitates the substantial reduction of reliance on fossil fuels, especially gas and coal. The financial prospects of biomass of agricultural origin for energy production in Ukraine is almost 9 million tons of oil equivalent, which is equal to 43% of the total potential of biomass (20.9 million tons of oil equivalent). At the same time, the amount of available biomass tends to increase, which is important for ensuring the stability of the fuel supply in the energy complex (Agri-gator, 2019).

The statement highlights the significant role biomass can play in Ukraine's energy sector, emphasizing its potential contribution both to energy production and economic impact. Specifically:

- *Potential Energy Production*. The figure of 9 million tons of oil equivalent (toe) represents nearly half (43%) of the total biomass energy potential in Ukraine, which is estimated at 20.9 million toe. This indicates a substantial reserve of energy that can be harnessed from biomass, equivalent to approximately 9% of Ukraine's current total primary energy supply (based on pre-war energy consumption levels). Increasing the use of biomass could significantly enhance Ukraine's energy security by reducing its dependence on imported fuels such as natural gas and oil. It could also serve as a stable source of renewable energy, diversifying the energy mix and contributing to a more sustainable and resilient energy system (Lutkovska and Zelenchuk, 2021).
- *Economic Impact*. The growing availability of biomass resources underscores its capacity to support the development of a domestic bioenergy industry. This can lead to job creation in rural areas, stimulate local economies, and attract investment in energy crop cultivation, biomass processing, and related infrastructure. Leveraging this potential could generate significant cost savings by replacing imported fossil fuels with domestically produced biofuels. It also opens opportunities for exports of bioenergy products, such as pellets and biogas, to international markets, enhancing Ukraine's trade balance (Heletukha, 2022).
- *Stability of Fuel Supply*. The increasing availability of biomass ensures a reliable and scalable source of fuel, crucial for the stable operation of the energy complex. Unlike fossil fuels, biomass resources can be replenished continuously through agricultural and forestry activities, offering long-term sustainability. This stability is particularly important in the context of Ukraine's ongoing energy challenges, as it reduces vulnerabilities to geopolitical disruptions and supply chain uncertainties (Pryshliak, 2021a).

In summary, the figure highlights biomass as a key renewable energy resource for Ukraine, with the potential to contribute significantly to energy independence, environmental sustainability, and economic growth. One of the important sources of biomass in Ukraine is forest waste – branches, bark, and brush, which can be processed into fuel briquettes or pellets. The country's forested land covers more than 10 million hectares, which provides great opportunities for the use of wood and forest biomass.

However, the forest sector of Ukraine faces serious challenges that threaten its sustainable development. The worldwide shift towards eco-friendly energy highlights the urgency of addressing these issues to fully realize the sector's potential. According to estimates, Ukraine uses more wood for energy needs than it has time to regenerate. Thus, in 2023, the excess level of wood use amounted to 36%, which is an alarming trend for the future of the country's forest resources. Today, about 50-70% of forest biomass is harvested independently or illegally, and there is an imbalance in the market. Major types of biomasses, such as firewood and logging waste, are overused, while secondary resources such as wood chips and pellets are either not fully exploited or exported due to market distortions. Forest biomass is actively used by households, which consume about 55-60% of all resources, but the environment is significantly polluted due to outdated heating systems. This is a result of energy scarcity and the absence of alternative options (Budrin, 2023).

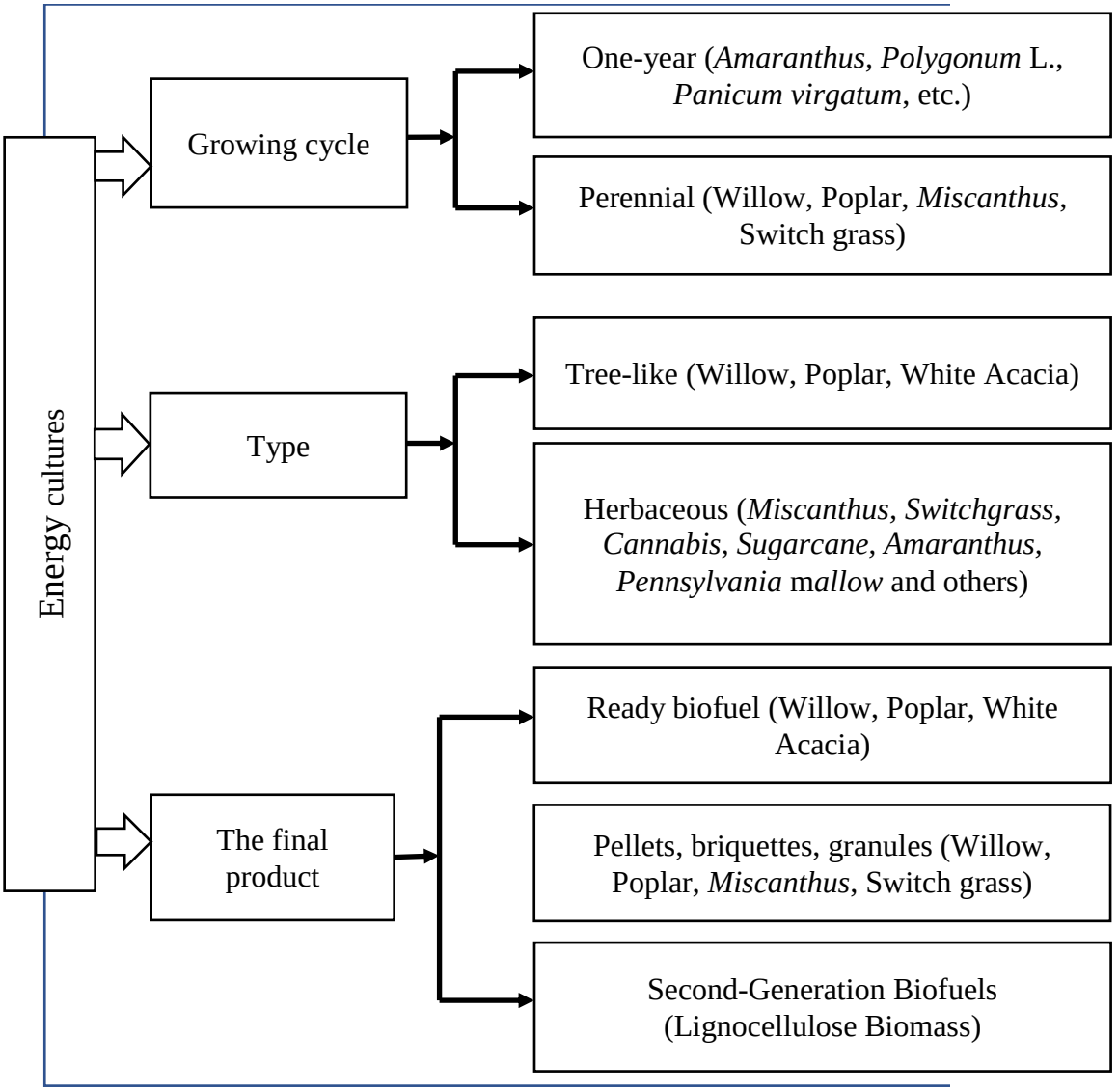
Energy cultures
Growing cycle
One-year (*Amaranthus, Polygonum* L., *Panicum virgatum*, etc.)
Perennial (Willow, Poplar, *Miscanthus*, Switch grass)
Type
Tree-like (Willow, Poplar, White Acacia)
Herbaceous (*Miscanthus, Switchgrass, Cannabis, Sugarcane, Amaranthus, Pennsylvania* m*allow* and others)
The final product
Ready biofuel (Willow, Poplar, White Acacia)
Pellets, briquettes, granules (Willow, Poplar, *Miscanthus*, Switch grass)
Second-Generation Biofuels (Lignocellulose Biomass)

Figure 1. Characteristics of energy crops [*Source:* Pryshlyak, 2021a]

As noted by Hura (2024), Ukraine lacks a thorough regulatory framework for utilizing forest biomass for energy production. Existing regulations are fragmented, and their implementation is inconsistent. As of September 2024, sustainability criteria for biomass harvesting have not yet been implemented in the country, which limits the ability to meet EU standards and receive financial support. In addition, the process of forest and logging management remains time-consuming and poorly controlled, creating risks of abuse. Given the substantial potential of forest biomass to support national renewable energy targets, the sector requires extensive reforms, strategic planning, and the establishment of sustainability criteria for long-term development. Energy crops are plants that are specifically grown for use directly as fuel or for biofuel production. The general characteristics of energy crops for biofuel production are shown in figure 1.

Energy crops, unlike food crops, do not have special requirements for soil quality and can be grown on degraded lands. Among EU nations, Italy leads in land dedicated to energy plantations, covering 57,000 hectares, the highest in Europe. Following Italy are Poland with 13,000 hectares, Sweden with 12,000 hectares, Germany with 11,000 hectares, Denmark with 10,000 hectares, and Finland with 8,000 hectares (Eurostat, 2020).

The Raw Material Base of Ukrainian Bioenergy

Energy crops are usually low in chemical elements and high in lignin and cellulose, and some species are also rich in sugar and starch. This makes them an ideal resource for producing energy-efficient biofuels. The possibility of increasing the amount of cultivation of such crops depends to a large extent on the availability of land, as it is crucial to simultaneously address the rising global food demand, preserve the environment, ensure the sustainable use of soil and water resources, and also meet other requirements of sustainable development. Heletukha (2022) highlights the following advantages of growing energy crops in Ukraine:

- substitution of imported energy resources with own energy sources;
- improvement of the country's trade balance due to a decrease in imports;
- creation of new jobs, which contributes to the employment of the population;
- assistance in fostering the growth of the local economy;
- ensuring a stable and predictable source of biofuel;
- the potential of annual replacement of up to 8.9 billion m^3 of gas at the expense of biofuel;
- reducing the level of greenhouse gas emissions;
- restoration of soil fertility thanks to the use of certain types of crops;
- a large stock of land resources for cultivation (up to 4 million hectares);
- the ability to accumulate solar energy (energy crops act as a kind of natural "accumulators" that collect and store solar energy, transforming it into a form that can be used to obtain energy for human needs) (Heletukha, 2022).

In Ukraine, more than 20 types of fast-growing energy crops, which are promising for growing to obtain plant biomass, are currently being studied. These crops include fast-growing trees, including varieties of willow and poplar, as well as annual and perennial grasses, such as sorghum, sugarcane, *Miscanthus*, amaranth, *Pennsylvania mallow*, *Rumex*, millet, hybrid tobacco, and others. Today, the area of energy plant plantations in Ukraine is about 6.4 thousand hectares, of which the largest areas are occupied by willow (about 3 thousand hectares) and *Miscanthus* (about 2 thousand hectares) (Pryshlyak, 2021b).

The Department of Selection and Sustainable Technologies for Growing and Processing Bioenergy Crops of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine is constantly working on the development of new varieties of bioenergy plants and implementing sustainable methods of their cultivation. The priority crops include: sugar and fodder beets, sugar and grain sorghum, *Miscanthus*, switchgrass (rod-like millet), willow, poplar, acacia and paulownia. In recent years, new *Miscanthus* varieties have been included in the State Register ("Osinniy Zoretsvit", "Snizhna Koroleva" ", "Misiachnyi Promin"), switchgrass ("Morozko", "Liadovske") and willow ("Zbruch") (Hanzhenko, 2020).

8 million hectares of Ukraine's agricultural land are deemed unproductive or marginal out of the total area suitable for cultivation (Heletukha, 2017; Savchuk, 2024). About 3.5 million hectares of these lands are excluded from crop rotation due to low fertility, susceptibility to erosion, excessive moisture and other unfavourable conditions (Blum, Geletukha & Grigoryuk, 2010). Cultivation of fast-growing, high-yielding energy crops on these lands will help protect soils from erosion, increase humus content, and generally contribute to improving the country's ecological and energy balance.

In Ukraine, there is great potential for energy production from livestock waste, such as manure and poultry droppings, by obtaining biogas. Biogas can be used to generate electricity and heat or as a substitute for natural gas. Currently, the large volumes of waste on the country's industrial farms are causing environmental problems that require solutions. Converting these wastes into biogas will not only help address environmental challenges but also enable the decentralized production of renewable energy and fuel. Livestock waste is particularly suitable for biogas production because, unlike energy crops, manure and droppings are by-products that require ecological disposal. Moreover, manure can be easily mixed with other substrates, such as plant silage, including corn.

Studies show that anaerobic fermentation of manure and droppings contributes to reducing the risks of soil and water pollution, lowering the volume of emissions released into the atmosphere, and reducing the negative impact on the climate. Thanks to such processing, the level of nitrogen and phosphorus pollution is reduced, which reduces threats to drinking water sources and wetlands. Also, anaerobic fermentation significantly reduces the intensity of the smell, minimizing its effect on the local community (Martsynkevych and Kolomiiets, 2015). A promising raw material for bioenergy is the remains of food and agro-industrial production, in particular, waste from the processing of sugar beets and oil crops. These wastes can be utilized to produce biogas, bioethanol, and even solid fuel. Sugar beet pulp is rich in organic substances suitable for anaerobic fermentation. Extracts of oil crops, such as sunflower or soybean meal, are also high-calorie raw materials suitable for pyrolysis or gasification, which turns them into synthetic gas or biochar. Ukrainian breeders of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine are already carrying out selection work to create specially adapted types of sugar beet intended for the needs of the energy industry. Sugar beet biomass is saturated with sugars and can easily be processed into bioethanol. In addition, due to the increased content of dry matter, sugar beets can be processed into biogas (Kudril, 2019).

Biomass Conversion Technologies for Energy

Among the main technologies for converting biomass into energy, which allow for obtaining different types of fuel and energy, the following should be highlighted: anaerobic fermentation, pyrolysis, gasification, combustion, fermentation, and esterification. Anaerobic fermentation is used to process organic waste (manure, food waste, agricultural waste), which in the absence of oxygen is decomposed by bacteria with the formation of biogas. Biogas is generated through the process of methane fermentation, where organic materials derived from plants and animals are broken down in specialized biogas facilities. Based on Samoichuk (2020), 1 ton of dry organic raw

materials can be obtained from 350 to 400 m³ of biogas, which has a calorific value of 23-25 MJ/m³. In practical terms, 1 m³ of biogas has the potential to substitute 4 kWh of electrical energy or around 1.5 kg of solid coal.

The essence of pyrolysis consists of heating biomass at high temperatures without air access, which leads to its decomposition into solid residue (biochar), liquid products (pyrolytic oil) and synthetic gas. This process makes it possible to obtain high-calorie solid fuel (biochar) and liquid biofuel, which serves as a viable substitute for petroleum-based products (Daniuk and Boltianska, 2020). Gasification is the partial oxidation of biomass at high temperatures, which leads to the formation of synthesis gas (containing hydrogen, carbon monoxide and other combustible gases). Syngas can be used to produce electricity and heat or as a feedstock for the synthesis of liquid fuels (e.g. bioethanol or biodiesel). Syngas can be produced from almost any organic material, including biomass and organic waste. In recent decades, the global scientific and engineering community has achieved significant success in advancing cutting-edge approaches to the gasification of raw materials with carbon content. Modern technologies of thermochemical processing make it possible to transform waste and biomass into high-quality synthetic products, reducing the release of carbon emissions into the air and accumulation of waste in landfills. According to Kolisnyk (2023), this opens up great opportunities to advance the growth of Ukraine's chemical industry, especially taking into account the needs of post-war reconstruction.

Combustion (integrated production of heat and electricity) is the simplest and most widespread method in which biomass is burned to produce heat energy that can be used both for heating and for generating electricity within cogeneration systems that combine heat and power production. Cogeneration enhances overall energy efficiency and lowers fuel and energy resource costs compared to producing heat and electricity separately. In the countries of the European Union, there are various incentives to support the development of cogeneration technologies, which are quite flexible and regularly adapt to changes in the market situation (Heletukha, Zhelezna and Bashtovyi, 2019).

Fermentation is used to produce bioethanol from biomass containing sugars or starch (such as corn, sugar beets, and sugar cane). In this process, yeast converts sugars into ethanol. Based on the findings of experts from the Ukrainian technology company, bioethanol, which is used as a fuel for transport in the form of a mixture with gasoline, contributes to an increase in the total octane number, improves the efficiency of the engine, increases the oxygen content in the fuel to 3.7% and significantly reduces emissions of harmful substances, such as benzopyrenes, dioxins and carcinogens. Worldwide, 82% of ethanol is utilized as fuel, 9% serves industrial purposes, and the remaining 9% is used in the alcoholic beverage sector (Lukashevych, 2020).

The essence of esterification is the processing of vegetable oils and fats into biodiesel, which is obtained by the chemical reaction of fatty acid esters with methanol or ethanol, and it is used as an ecological alternative to diesel fuel. These biomass-to-energy technologies enable the utilization of diverse waste and agricultural by-products for producing eco-friendly fuel, reducing reliance on fossil fuels, and supporting greenhouse gas emission reductions and sustainable energy industry development. The growth of energy production from biomass will help reduce Ukraine's dependence on gas imports,

which is one of its main geopolitical and economic problems. According to Kyryliuk (2023), Ukraine has enough biomass to completely replace 10 billion cubic meters of imported natural gas by 2030 and promote energy self-sufficiency by advancing bioenergy initiatives. In addition, the country can substitute 22 million tons of coal imports and 1 million tons of gasoline. By replacing imported energy carriers, Ukraine will have the opportunity to make notable improvements to its trade balance and develop biofuel exports.

Substituting fossil fuels with biomass contributes to lowering greenhouse gas emissions and minimizes environmental harm. Among the main advantages of plant biomass as a source of energy are significantly lower emissions of harmful substances compared to traditional types of fuel and the prevention of any disruption to the carbon dioxide balance in the atmosphere. During the burning of biofuel from plant biomass, less CO_2 enters the atmosphere than plants absorb during photosynthesis, and 20-30 times less sulfur compounds and 3-4 times less ash are formed compared to coal (Roik, 2020).

Advantages of Bioenergy Development in Ukraine

Bioenergy can stimulate the development of rural areas and become an additional source of income for agricultural enterprises. The creation and utilization of biofuels can provide agriculture with its energy resources, reducing fuel costs. (Pryshliak, 2021b). As world experience shows, biofuel production is a profitable opportunity for the economy of any country, as it plays a role in generating new employment opportunities. According to Habrel's calculations, the production of 1,000 tons of biofuel in oil equivalent provides about 16 jobs, mostly in rural areas. In Ukraine, each percentage of biofuel in the total volume of fuel consumption can create from 45 to 75 thousand new jobs in rural regions (Habrel, 2011). The Bioenergy Association of Ukraine has developed the "Road Map for the Development of Bioenergy of Ukraine until 2050", which envisions a substantial rise in the energy utilization of agro-biomass (Heletukha, 2021). Implementation of the Roadmap will require investments in the amount of 21-33 billion euros and is expected to replace approximately 20 billion cubic meters of natural gas per year, while also generating over 160,000 jobs by 2050 (Table 1).

Table 1: Projections for key bioenergy development indicators in Ukraine through 2050

Year	Biofuel consumption, million tons of oil equivalent	Replacement of natural gas, bln. m^3	Displacement of gasoline and diesel fuel, mln. tons	Reduction of CO_2 emissions, million tons/year	Investment, billion Euro		Creation of new jobs, units
					Min.	Max.	
2030	8.57	9.11	0.39	21.35	7.07	11.44	54300
2035	12.01	12.62	0.50	30.37	10.78	17.43	86200
2040	15.13	15.77	0.67	38.66	14.15	22.85	115400
2045	17.64	17.98	0.96	45.79	16.94	27.38	139000
2050	20.28	19.92	1.23	54.40	19.70	31.81	162700

Source: Heletukha (2021)

As reported by the International Renewable Energy Agency (IRENA), the global workforce in the renewable energy sector grows annually. Almost 66% of all employees in "green" energy are in Asian countries, where China's share is 42%. The USA and India each have 7% of jobs in this field, and the share of EU countries is 9.4% or 1.2 million jobs. In Europe, employment is distributed as follows: 314,000 people work in bioenergy, 298,000 in wind energy, and 235,000 in solar energy (Ukrainian Energy, 2023). Ukraine has demonstrated notable successes in implementing bioenergy projects, showcasing the potential of the sector to contribute to energy independence and sustainability. Key examples include:

- *Biogas Production.* Large-scale agricultural enterprises, such as MHP Eco Energy and Astarta-Kyiv, have established biogas plants utilizing agricultural residues and animal waste. These facilities not only generate electricity and heat but also reduce greenhouse gas emissions and provide organic fertilizers as a byproduct (Dombrovskyi, 2020).
- *Wood Biomass Utilization.* Municipalities, particularly in Western Ukraine, have replaced natural gas with wood chips and pellets for district heating. Projects like the bioenergy initiatives in Lviv and Ivano-Frankivsk regions demonstrate the cost-effectiveness and sustainability of using local biomass for energy needs (UNECE, 2023).
- *Industrial Bioenergy.* Ukrainian companies have integrated biomass boilers into their production processes, using wood residues to meet energy needs. This helps reduce waste and lower energy costs (Heletukha, 2017).
- *Energy Crops.* Pilot projects involving the cultivation of energy crops, such as willow and *Miscanthus*, have been successfully implemented in various regions. These crops are used as feedstock for biofuel production and have proven effective in rehabilitating degraded lands (Hanzhenko, 2020).

These projects highlight the economic, environmental, and energy security benefits of bioenergy, serving as a foundation for scaling up renewable energy initiatives in Ukraine. In addition, investments in bioenergy support the advancement of cutting-edge technologies and innovations, which stimulates overall technological progress. This, in turn, can benefit other sectors of the economy as well (Pecheniuk, 2024). A compelling reason to support the growth of bioenergy in Ukraine is the presence of almost 8 million hectares of unproductive land that can be used for growing perennial energy crops. According to experts' calculations, 2 million hectares of such land would be enough to completely replace gas in heat generation. To completely replace imported energy carriers with biofuels, approximately 3 million hectares need to be allocated for bioenergy crops, which is approximately 37% of all available low-productivity lands (Hadzalo, 2018).

It is important to highlight that the advancement of bioenergy in Ukraine is hampered by several objective and subjective reasons, among which we can highlight: insufficient level of financing of the industry, lack of effective stimulating legislative initiatives and limited technology, and lack of proper infrastructure. The absence of clear regulations governing the energy sector, along with intense competition from imported energy, also hinders the growth of the industry. The large-scale war initiated by the Russian Federation against Ukraine in 2022 led to a sharp decrease in the investment attractiveness of the bioenergy industry, and complex tax and regulatory conditions only

complicate the situation (Pecheniuk, 2024). In addition, Ukraine lacks modern technologies for optimal production and use of biomass, as well as infrastructure such as transport networks, state-of-the-art processing facilities and bioenergy plants. Some areas of bioenergy production can negatively affect the environment (for example, cutting down forests to obtain wood biofuel), which requires a balance between energy needs and environmental protection. The economic efficiency of bioenergy production in some cases is also inferior to traditional energy production (Pecheniuk, 2024). Projects that use biomass boilers or biogas plants for electricity generation often have high initial costs for equipment and infrastructure installation. The cost of biogas plants or biomass boilers can significantly exceed that of traditional thermal power plants that run on coal or natural gas. Furthermore, biomass as a raw material can be more expensive or less accessible compared to traditional energy sources like gas or coal, which can reduce the economic viability of bioenergy projects in the short term. For example, studies show that the cost of producing electricity from biomass can be 20-30% higher than from traditional energy sources due to high capital costs and expenses for transportation and processing of biomass. While traditional energy sources like gas or coal offer greater price stability and availability, bioenergy requires additional investments in technology development, raw material collection, and processing (Tsybulska, 2019). However, in the long term, bioenergy can become economically advantageous due to reduced costs for imported energy resources, the creation of new jobs in rural areas, and infrastructure development. Therefore, while bioenergy may initially lag behind traditional energy sources in terms of economic efficiency, its advantages become more evident over time, particularly in the context of energy security and sustainable development.

The development of bioenergy can create issues related to land use and food security. Specifically, extensive use of land for growing energy crops can reduce the area available for food production. This may lead to competition between energy production and food production, especially in the context of limited land resources. Additionally, monocultures of energy crops can deplete soils and worsen biodiversity. On the other hand, to maintain food security, bioenergy production must use agricultural waste (such as crop residues and organic waste), which reduces pressure on land while preserving its potential for food production.

Ways of Realizing Bioenergy Potential in Ukraine

To ensure the proper development of bioenergy, Ukraine should consider the best practices and experiences from around the world that implement state programs to support the industry. The primary methods for encouraging the growth of bioenergy production include:

- compensations from the state and local budgets to cover part of the capital costs associated with investments in bioenergy (capital subsidies, grants or discounts);
- tax credits (investment or production);
- reduction of tax rates on the acquisition or development of technologies for utilizing bioenergy solutions;

- state investments, loans or grants for infrastructure development and implementation of projects in bioenergy (Denysenko, 2020).

The outcome of fostering bioenergy development in Ukraine should be achieving a balance between the expected economic effect and the impact on the social and environmental situation in the regions of the country (Hryhoruk, 2020). In addition to financial support and tax incentives, an appropriate set of measures needs to be implemented:

- development of bioenergy infrastructure (funding the establishment and modernization of infrastructure for the collection, processing and transportation of biomass, creation of local biowaste processing hubs that will ensure the supply of raw materials to processing enterprises) (Pryshliak, 2021b);
- regulatory measures: Streamlining licensing and permitting procedures for bioenergy projects, developing and implementing national standards and technical requirements for bioenergy installations, and ensuring adherence to environmental regulations and standards;
- information support: Promoting the industry's growth through public and business outreach campaigns to raise awareness of bioenergy, and disseminating information on the best international practices and cutting-edge technologies in the bioenergy sector;
- scientific and innovative support: Funding research initiatives aimed at improving the efficiency of bioenergy technologies and providing support to startups and innovative companies within the bioenergy sector;
- enhancing global cooperation in the bioenergy sector: Attracting international investors and partners to advance bioenergy projects in Ukraine, participating in global exchange programs for sharing experiences and technologies, and leveraging global best practices to stimulate the development of the domestic bioenergy industry.

These measures will help speed up the advancement of bioenergy in Ukraine, and increase its economic efficiency (diversification of the resource base of energy, the substitution of imported media, production of stable and predictable energy, balancing of the energy system, diversification of agricultural production, development of innovations), promote ecological stability in the regions (decrease in human-induced environmental impact) and socio-economic development (creation of new jobs) (Stepanenko and Loktionov, 2024).

Conclusions

The research conducted highlights the potential of developing the bioenergy industry in Ukraine, which is due to the existing natural, resource, technological and human potential. The research highlights the significant potential of bioenergy development in Ukraine, underpinned by its natural, resource, technological, and human capital. Bioenergy can substantially reduce Ukraine's reliance on imported energy sources, particularly natural gas, which enhances the country’s energy security and strengthens economic stability. By diversifying the energy mix and decreasing dependence on

traditional fossil fuels, bioenergy contributes to both national energy independence and environmental sustainability.

The development of the bioenergy sector brings socio-economic benefits, including job creation, especially in rural areas, and infrastructure growth. Biomass helps reduce greenhouse gas emissions and supports Ukraine's international CO_2 reduction commitments, aligning with global sustainability goals. However, advancing bioenergy in Ukraine requires legislative support, tax incentives, grants, and foreign investments. Additionally, improving biomass processing technologies and biofuel production efficiency will lower costs and expand market opportunities for bioenergy products. To fully unlock the potential of the bioenergy sector, Ukraine must continue to strengthen its legislative framework, invest in modern technological infrastructure, and build the necessary bioenergy supply chains. These efforts will ensure the sustainable and efficient development of bioenergy, establishing it as a key component of Ukraine's energy system and contributing to its long-term energy security. In summary, the strategic development of bioenergy holds immense promise for Ukraine, provided that the challenges related to legislation, technology, and infrastructure are effectively addressed.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*	*Author 6*	*Author 7*
Conceived and designed the research or analysis	Yes	Yes	No	No	No	No	No
Collected the data	Yes	Yes	No	Yes	Yes	No	No
Contributed to data analysis & interpretation	No	No	Yes	No	No	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	Yes	No	No	Yes	No
Editing of the article/paper	Yes	No	No	No	No	No	Yes
Supervision	Yes	Yes	No	No	No	No	No
Project Administration	Yes	No	No	No	No	No	No
Funding Acquisition	No	No	No	No	No	No	No
Overall Contribution Proportion (%)	16	14	14	14	14	14	14

Funding
No financial support was received for the research and writing of this article.

Research involving human bodies or organs or tissues (Helsinki Declaration)
The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children
The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)
The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

Competing Interests/Conflict of Interest
Author(s) has/have no competing financial, professional, or personal interests from other parties or in publishing this manuscript. There is no conflict of interest with the publisher or the editorial team or the reviewers.

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